On-orbit Characterization of a Solar Diffuser s Bi-directional Reflectance Factor Using Spacecraft Maneuvers

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ABSTRACT

The MODerate Resolution Imaging Spectroradiometer (MODIS) uses an on-board solar diffuser (SD) panel made of Spectralon for the radiometric calibration of its 20 reflective solar bands (RSB). The spectral wavelengths of the RSB range from 0.41 to 2.1 micrometers. The on-orbit calibration coefficients are determined from the sensor s responses to the diffusely reflected solar illumination from the SD. This method requires an accurate pre-launch characterization of solar diffuser s bi-directional reflectance factors (BRF) that should cover the sensor s spectral range and illumination/viewing angles and accurate on-orbit monitoring of SD degradation over time. The MODIS SD panel s bi-directional reflectance factors were characterized prior to the sensor s final system integration (pre-launch) by the instrument vendor using reference samples traceable to the NIST reflectance standards at a number of wavelengths and carefully selected combinations of the illumination/viewing angles. The measured BRF values were fitted into smooth surfaces and then interpolated for each of the MODIS reflective solar bands. In this paper, we describe an approach designed for the MODIS on-orbit characterization and validation of its SD BRF using multiple SD solar observations at several spacecraft yaw angles. This approach has been successfully applied to both the Terra and Aqua MODIS. This paper presents the algorithm used to derive the SD s relative BRF from observations during spacecraft yaws and compares the on-orbit results with corresponding pre-launch values.

Keywords: MODIS, solar diffuser, calibration, BRF, Terra, yaw maneuvers

1. INTRODUCTION

Solar diffusers (SD) are often used in the Earth observing remote sensing satellites for their on-board radiometric calibration of visible (VIS) and near infrared (NIR) spectral bands and also widely used in the ground validation measurements in support of the sensors on-orbit observations[1-6]. For these sensors, the calibration accuracy strongly depends on the knowledge of the SD s bi-directional reflectance factor (BRF) and on the information pertaining to any SD degradation during the satellites on-orbit operation.

The MODerate Resolution Imaging Spectroradiometer (MODIS), one of the key instruments for the NASA s Earth Observing System (EOS), is currently operating on the EOS Terra and Aqua satellites[7-8]. The MODIS on the EOS Terra is the Protoflight Model (PFM) while the EOS Aqua carries the MODIS Flight Model 1 (FM1). Each MODIS has 36 spectral bands, making observations at three different nadir spatial resolutions: 250m for bands 1-2, 500m for bands 3-7, and 1.0km for bands 8-36. These bands are carefully selected to provide global monitoring of the Earth s land, oceans, and atmosphere properties from space. The instrument design and spectral bands selection were based on heritage sensors such as the Advanced Very High Resolution Radiometer (AVHRR), the Landsat Thematic Mapper (TM), the Nimbus 7 Coastal Zone Color Scanner (CZCS), and the High Resolution Infrared Radiation Sounder (HIRS).

MODIS bands 1-19 and 26 cover the spectral range of visible (VIS), near infrared (NIR), and short-wave infrared (SWIR). These bands are known as the reflective solar bands (RSB) with center wavelengths located from 0.4 to 2.1 micrometers. The remaining 16 spectral bands with wavelengths above 3.5 micrometers are known as the thermal emissive bands (TEB), and span the spectral range from the mid-wave to long-wave infrared (MWIR and LWIR). Each

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MODIS scan collects data from five sectors, three of which are from its on-board calibrators: solar diffuser (SD), spectroradiometric calibration assembly (SRCA), and blackbody (BB). The fourth sector collects data from the instrument s space view, providing information on the sensor s background response needed for the on-orbit calibration, and the fifth sector contains measurements of the Earth scenes. The SD is used for the RSB calibration and the BB for the TEB calibration. The SRCA is primarily used for the instrument s spatial and spectral characterization. A number of references have presented detailed descriptions of the MODIS on-orbit radiometric calibration of RSB and TEB, and the sensor s spatial and spectral characterization, including the calibration methodologies and actual performance[9-13].

The MODIS solar diffuser s bi-directional reflectance factor (BRF) was characterized pre-launch by the instrument vendor, Raytheon Santa Barbara Remote Sensing (SBRS) at Goleta, CA, using reference samples traceable to NIST reflectance standards[14-15]. An on-board solar diffuser stability monitor (SDSM) is used together with the SD observations to track its on-orbit degradation. In this paper, we review the pre-launch characterization of the SD BRF and present an approach designed for on-orbit BRF characterization and validation. This approach takes advantage of the spacecraft s maneuvering capability to map the SD s relative BRF using the MODIS detectors on-orbit response during carefully planned spacecraft yaw maneuvers. The results derived from the yaw maneuvers are compared with pre-launch values.

2. MODIS PRELAUNCH SOLAR DIFFUSER BRF CALIBRATION

On-orbit calibration of the MODIS reflected solar bands (RSB) is achieved using an on-board solar diffuser (SD) plate comprised of space grade spectralon", a near perfect Lambertian diffuser. For each of the MODIS instruments, the bi-directional reflectance distribution function (BRDF) or the bi-directional reflectance factor (BRF) of the SD panel was characterized pre-flight using reference diffuser samples traceable to the NIST (National Institute of Standards and Technology) reflectance standards. Figure 1 shows the MODIS solar diffuser panel. As described in references 14 and 15, the pre-flight SD measurements were made using a scattering goniometer in a comparison mode. The scattering goniometer was characterized by the reference samples with know BRF properties.

Figure 1: MODIS on-board solar diffuser panel used for the reflective solar bands on-orbit calibration.

The SBRS SD calibrations were performed at five wavelengths from 0.4 to 1.7 micrometers over a two-dimensional grid of nine directions of incidence (3 elevation angles and 3 azimuth angles). The directions of incidence covered the anticipated angular range that would be observed during instrument flight. The viewing direction was fixed, corresponding to the sensor s SD view via the scan mirror. In order to use the pre-launch characterization for on-orbit applications, interpolation of the measurement results was necessary for each of the wavelengths and all possible incident directions (the solar zenith and azimuth angles: θ and ϕ) to be used on-orbit. Therefore, for each characterized spectral wavelength, a second order polynomial function (of incident directions) was determined from the pre-launch (PL) measured BRF values,

$$BRF_{\lambda}^{PL}(\theta_{SD},\phi_{SD}) = a_0 + a_1\theta_{SD} + a_2\phi_{SD} + a_3\theta_{SD}^2 + a_4\phi_{SD}^2 + a_5\theta_{SD}\phi_{SD} \quad (1)$$

where the coefficients depend upon the wavelength. The fitting results are listed in Table 1 for both the Terra and Aqua MODIS SD panels.

The measured wavelengths do not correspond directly to the MODIS spectral bands. Therefore, for each incidence direction the BRF is linearly interpolated to the wavelengths of the MODIS bands. This algorithm is used for 19 of the 20 RSBs. No direct BRF measurements were made near 2.1 micrometers, which is the center wavelength of MODIS band 7. At the time of preflight calibration and characterization, the reference samples BRF property at this wavelength was not available due to measurement limitation. The BRF of band 7 was later indirectly derived from BRDF at other wavelengths and the reference samples total integrated scattering (TIS) measurements at many other wavelengths, including 2.1 micrometers. The calibration accuracy specification for the MODIS Level 1B (L1B) reflectance product is 2%. The most dominant terms in the L1B reflectance product s error budgets came from the pre-launch SD BRF characterization[14-15].

Terra	a_0	a_1	a_2	a_3	a_4	a_5
400nm	0.854132	0.393845	-0.044134	-0.241091	-0.008503	0.053395
500nm	0.654293	0.815651	0.035889	-0.460631	-0.030213	-0.039109
600nm	0.754483	0.620948	-0.002219	-0.364208	-0.020965	0.005794
900nm	0.929442	0.262861	-0.037498	-0.185772	-0.021398	0.038721
1700nm	0.686956	0.757221	0.042981	-0.437603	-0.032427	-0.050642
Aqua	a_0	a_1	a_2	a_3	a_4	a_5
400nm	0.839706	0.445004	-0.001284	-0.284564	-0.025309	-0.003512
500nm	0.971627	0.152939	-0.064211	-0.122074	0.002502	0.079574
600nm	0.969569	0.213631	-0.032944	-0.161179	-0.007791	0.042231
900nm	0.955451	0.211436	-0.012514	-0.162862	-0.014670	0.016150
1700nm	0.854570	0.430864	0.005843	-0.286285	-0.035937	-0.024730

Table 1: Pre-launch BRF coefficients of MODIS solar diffuser panel derived from a quadratic surface fitting.

3. ON-ORBIT CHARACTERIZATION DATA FROM YAW MANEUVERS

The MODIS L1B primary data product for the reflective solar bands (RSB) is the earth view (EV) reflectance factor, $\rho_{EV}\cos(\theta_{EV})$, which is given by

$$\rho_{EV}\cos(\theta_{EV}) = m_1 \cdot dn_{EV}^{*} \cdot d_{ES}^2 \quad (2)$$

where θ is the solar zenith angle, m_1 is the calibration coefficient determined by the SD and SDSM observations, d_{ES} is the Earth-Sun distance in AU at the time of the Earth view measurement, and dn^*_{EV} is the background subtracted, scan mirror reflectance, and instrumental temperature effect corrected digital number. This calibration is performed for each pixel depending on the band, detector, sub-sample, and mirror side (BDSM). Using the SD observation, the calibration coefficient, m_1, can be computed by

$$m_1 = \frac{\rho_{SD}\cos(\theta_{SD})}{dn_{SD}^{*} \cdot d_{ES}^2} \quad (3)$$

where ρ_{SD} is the SD BRF, dn^*_{SD} is the corrected detector response to the SD view, and d_{ES} here is the Earth-Sun distance in AU at the time of the SD measurements. Not shown in Eqn. 3 is a SD degradation factor determined on-orbit by the SDSM[16]. For some high gain bands (8-16) that saturate when directly viewing the SD reflected sunlight, a retractable SD screen (SDS) is used. Therefore, for these bands, a SDS vignetting function has to be included in the calibration equation.

The on-orbit BRF characterization approach uses Eqn. 2 and the SD observations over a complete range of illumination angles that would be used in the normal SD calibration. This approach directly uses the MODIS bands/detectors that do not saturate when no SD screen is used (bands 1-7, 17-19, and 26). The on-orbit measurements provide relative BRF values from the MODIS detectors responses to SD illuminations at angles achieved through a sequence of yaw maneuvers at various solar azimuth angles. The spacecraft flight in any given orbit provides a range of elevation angles. Detailed descriptions of the algorithms used are provided in the next section.

Two sets of spacecraft yaw maneuvers have been conducted for the purpose of studying the Terra MODIS solar diffuser BRF and the SD screen s vignetting function. This paper focuses on the SD BRF measurement with the screen in the open position. The ratios of the screen down and up observations provide information for the SDS vignetting function. The first set of yaws was carried out on June 25, 2000. There were six yaws with the SDS in the open position, but only five have data available. The second set of yaws was implemented on December 5 and 11, 2002 to improve on the first set of measurements and also to examine the uniformity of the SD BRF degradation. There are a total of 16 yaws, of which four are with angles equal to zero. Table 2 lists the slew angles and the corresponding solar azimuths of the second set of yaws used for the SD BRF study. The SWIR bands (5-7 and 26) are excluded from BRF characterization to avoid additional uncertainties that might be introduced due to their detectors electronic crosstalk. Therefore the SD BRF is only characterized using MODIS bands 1-4, 17-19.

Date of Event mm/dd/yy	Data Collect Start Time	SolAZ at the mid-point of the collect without Yaw	Requested°Yaw Offset	Requested SolAZ at the mid-point of the collect
12/05/02	11:27:33	-22.04	0.00	-22.04
12/05/02	13:06:27	-22.04	8.96	-31.0
12/05/02	14:45:20	-22.05	5.75	-27.8
12/05/02	16:24:13	-22.06	2.54	-24.6
12/05/02	18:03:07	-22.06	-0.66	-21.4
12/05/02	19:42:00	-22.07	-3.87	-18.2
12/05/02	21:20:53	-22.08	-7.08	-15.0
12/05/02	22:59:46	-22.08	0.00	-22.08
12/11/02	10:50:43	-22.65	0.00	-22.65
12/11/02	12:29:36	-22.66	9.94	-32.6
12/11/02	14:08:29	-22.67	6.73	-29.4
12/11/02	15:47:22	-22.67	3.53	-26.2
12/11/02	17:26:15	-22.68	0.32	-23.0
12/11/02	19:05:08	-22.69	-2.89	-19.8
12/11/02	20:44:02	-22.70	-6.10	-16.6
12/11/02	22:22:55	-22.71	0.00	-22.71

Table 2: Listing of the critical information pertaining to Terra yaw maneuvers on December 5 and 11, 2002.

In Table 2, the data collection start time corresponds to the middle point of data collection time minus 6.3 minutes, SolAZ stands for the solar azimuth angle.

4. ON-ORBIT BRF RETRIEVAL ALGORITHM AND RESULTS

MODIS calibration is performed for each band, detector, sub-frame, and mirror side (BDSM). For a given detector, its response to the Sun illuminated SD, after corrections to the instrument background and temperature effects, is expressed as a digital number,

$$dn(B,D,S,M) = g(B,D,S,M) BRF_B(\theta_{SD},\phi_{SD}) \cos(\theta_{SD}), \tag{4}$$

where B, D, S, M is the band, detector, sub-frame, and mirror side index, g is a scaling factor that is also band, detector, sub-frame, and mirror side dependent, and θ_{SD}, ϕ_{SD} are solar zenith and azimuth of the incident sunlight, respectively, in the SD coordinate system. There are 50 samples of data in the SD sector each scan. The variation of θ_{SD}, ϕ_{SD} during the 50 sample collection period is negligible. To simplify the data process, we average all sub-frames and detectors within a band each scan. However we keep the mirror side dependency. Thus for each scan, Eqn. 4 becomes

$$dn_{avg}(B,M) = g_{avg}(B,M)BRF_{B,M}(\theta_{SD},\phi_{SD})\cos(\theta_{SD}), \tag{5}$$

The BRF is obviously independent of which scan mirror side is used. One of the reasons we treat each mirror side independently is that the data from the each mirror side belong to a different scan with different θ_{SD} and ϕ_{SD}. Similar to the pre-launch BRF function, we express the on-orbit BRF as a quadratic function of solar zenith and azimuth angles,

$$g_{avg}(B,M)BRF_{B,M}(\theta_{SD},\phi_{SD}) = b_0 + b_1\theta_{SD} + b_2\phi_{SD} + b_3\theta_{SD}^2 + b_4\phi_{SD}^2 + b_5\theta_{SD}\phi_{SD}. \tag{6}$$

We have kept the scaling factor together with the SD BRF since we can not separate them from on-orbit observations. At any given time, the scaling factor only depends on the detectors responses. The coefficients in Eqn. 6 can be determined by minimizing

$$y = \sum_i \left[g_{avg}(B,M)BRF_{B,M}(\theta_{SD}^i,\phi_{SD}^i) - dn_{avg}^i(B,M)/\cos(\theta_{SD}^i)\right]^2, \tag{7}$$

where the summation is performed over the scans corresponding to the sane mirror side M (M=1 or 2). The on-orbit BRF using coefficients derived from Eqn. 7 is a relative one. To normalize it to the pre-launch BRF for comparison purpose, the scaling factor for each mirror side can be calculated by

$$g_{avg}(B,M) = \sum_{\theta_{SD},\phi_{SD}} \left(b_0 + b_1\theta_{SD} + b_2\phi_{SD} + b_3\theta_{SD}^2 + b_4\phi_{SD}^2 + b_5\theta_{SD}\phi_{SD}\right) / \sum_{\theta_{SD},\phi_{SD}} BRF_B^{PL}(\theta_{SD},\phi_{SD}). \tag{8}$$

Table 3 lists the results of the scaling factors for Terra MODIS bands 1-4, and 17-19. The mirror side dependent scaling factor is related to the band averaged gain using the same mirror side at the time of BRF characterization. The ratio of mirror side 1 to mirror side 2 scaling factor is proportional to the ratio of band-averaged sensor s calibration coefficient from mirror side 2 to that from mirror side 1. Figure 2 shows the good agreement between the two ratios.

Band	Wavelength	g_{avg}(B,1)	g_{avg}(B,2)
1	646.5	2611.94	2632.21
2	856.7	3978.07	4018.01
3	465.6	4001.35	3975.04
4	553.7	4141.92	4163.60
17	904.1	5717.73	5774.57
18	935.3	4011.84	4049.03
19	936.1	5393.74	5443.58

Table 3: Summary of scaling factors derived from the Terra yaw maneuvers for the SD BRF characterization.

Finally the on-orbit relative BRF can be obtained by averaging the results from each mirror side

$$BRF_B(\theta_{SD},\phi_{SD}) = \frac{1}{2}\sum_M BRF_{B,M}(\theta_{SD},\phi_{SD}) \tag{9}$$

or

$$BRF_B(\theta_{SD},\phi_{SD}) = c_0 + c_1\theta_{SD} + c_2\phi_{SD} + c_3\theta_{SD}^2 + c_4\phi_{SD}^2 + c_5\theta_{SD}\phi_{SD}. \tag{10}$$

Now the quadratic coefficients for the normalized BRF only depend on the band. Table 4 summarizes the on-orbit relative (normalized) BRF coefficients derived for bands 1-4 and 17-19 using data from yaw maneuvers on December 5 and 11, 2002.

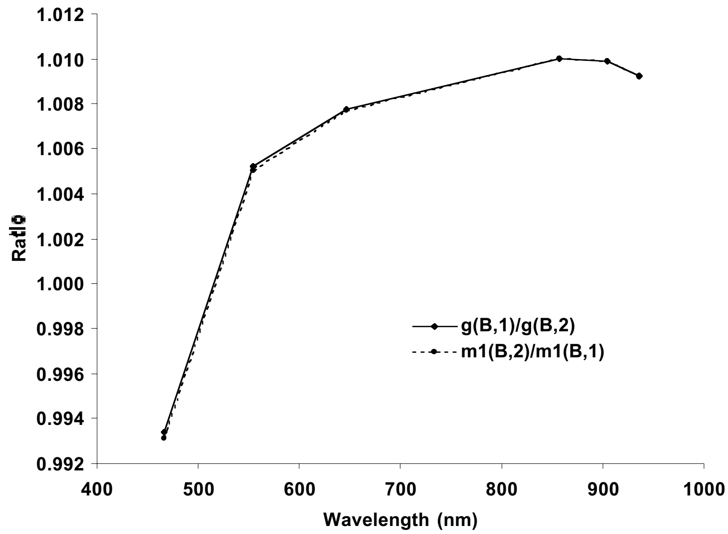

Figure 2: Comparison of mirror side dependent scaling factors with the calibration coefficients at the time of SD BRF characterization.

Band	Wavelength	c0	c1	c2	c3	c4	c5
1	646.50	0.805961	0.540443	0.013532	-0.334310	-0.021075	-0.007755
2	856.70	0.806196	0.509680	-0.010720	-0.311821	-0.034090	-0.000154
3	465.60	0.902842	0.334900	0.010339	-0.226995	-0.012383	-0.000508
4	553.70	0.947624	0.253836	0.013081	-0.188740	-0.013958	-0.002999
17	904.10	0.720158	0.685379	-0.007430	-0.397931	-0.029718	0.007149
18	935.30	0.896701	0.344997	0.010434	-0.234873	-0.029584	-0.012278
19	936.10	0.942313	0.256080	0.003316	-0.191262	-0.029808	-0.004870

Table 4: The on-orbit relative coefficients for the Terra MODIS SD BRF fitted as a quadratic surface.

5. COMPARISON OF PRE-LAUNCH AND ON-ORBIT BRF

We cannot directly compare coefficients in Table 4 with the pre-launch BRF coefficients listed in Table 1 since the wavelengths of the pre-launch measurements do not match the MODIS bands. We have to compare the pre-launch derived (interpolated) BRF for the corresponding MODIS band using the coefficients in Table 1 with the BRF from the coefficients listed in Table 4.

Figures 3-5 show the surface plots of on-orbit (relative) BRF for Terra MODIS B1, B3, and B18, respectively. For each band, the pre-launch and on-orbit relative BRF differences are also plotted over the interested viewing angles. The maximum differences in our interested range are smaller than 0.2%. Considering the fact that the pre-launch BRF characterization uncertainties for these bands are about 1.4-1.7% (0.7% due to spatial non-uniformity)[14-15], the agreement between the pre-launch and on-orbit characterization is excellent.

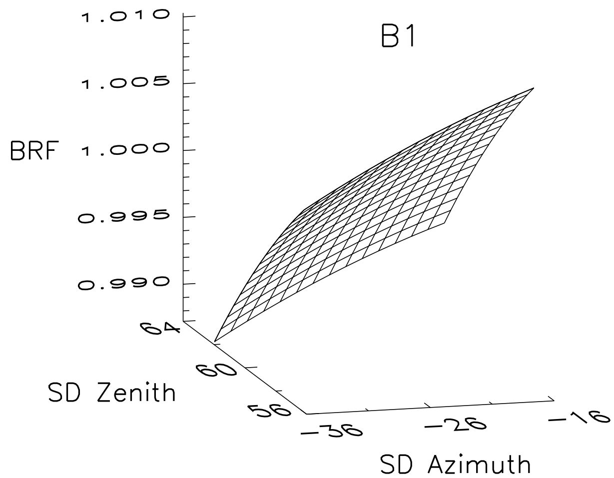

Figure 3: Comparison of pre-launch and on-orbit BRF for Terra MODIS band 1.

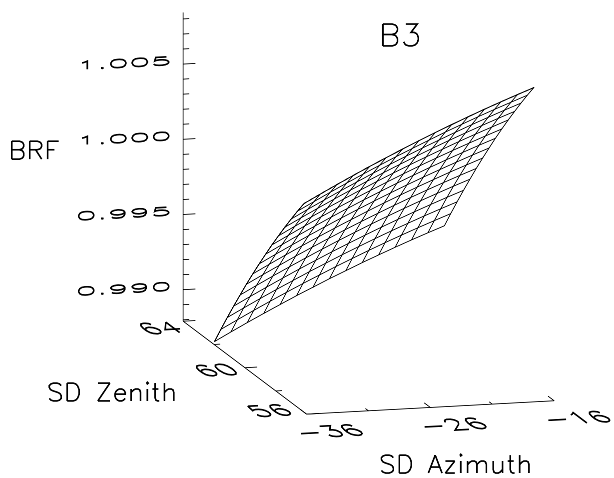

Figure 4: Comparison of pre-launch and on-orbit BRF for Terra MODIS band 3.

Using the same approach with the yaw data of June 25, 2000, we have derived the on-orbit relative BRF for B1-B4 and B17-B19. As expected, the results also match well with the pre-launch characterized BRF. It should be pointed out that the scaling constants from these two sets of yaws are different since both the reflectance of the scan mirror and the response of the MODIS detectors have changed significantly for some bands over the time between the two sets of yaw maneuvers. We can study the SD degradation over the 2.5 years between these two sets by comparing them directly. That is one of the reasons we requested the second set of yaws for the Terra spacecraft. The SD observations from the yaw maneuvers have shown that the SD degradation is very consistent with little variation over different illumination angles.

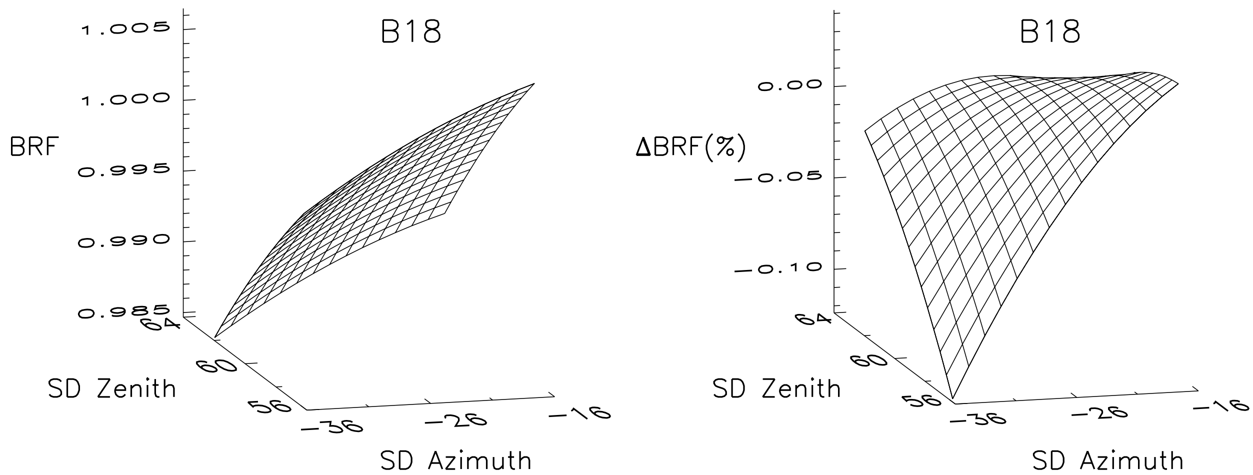

Figure 5: Comparison of pre-launch and on-orbit BRF for Terra MODIS band 18.

6. SUMMARY

Solar diffusers are often used for the on-orbit calibration of Earth-orbiting spectral radiometers. MODIS reflective solar bands from 0.41 to 2.1 micrometers are calibrated on-orbit by a solar diffuser (SD) and a solar diffuser stability monitor (SDSM) system. This paper provides an overview of the pre-launch characterization procedure for the MODIS solar diffuser s bi-directional reflectance factors (BRF) and results. It also presents an approach (algorithms and data processing) for the on-orbit characterization of SD BRF using the observations during carefully planned spacecraft yaw maneuvers. On-orbit relative BRF matches well with the pre-launch SD BRF, to within 0.15%. This implies that we have a firm understanding of the SD degradation as well as a reasonably good model of the BRF. We do not have validation of the on-orbit absolute BRF as this quantity cannot be measured on-orbit. Thus we will have to rely on the measured pre-launch BRF and constantly monitor the SD on-orbit degradation.

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